Chapter 5
Static and Dynamic Stress Analyses

5-1. Stress Analysis

a. General.

(1) A stress analysis of gravity dams is performed to determine the magnitude and distribution of stresses throughout the structure for static and dynamic load conditions and to investigate the structural adequacy of the substructance and foundation. Load conditions usually investigated are outlined in Chapter 4.

(2) Gravity dam stresses are analyzed by either approximate simplified methods or the finite element method depending on the refinement required for the particular level of design and the type and configuration of the dam. For preliminary designs, simplified methods using cantilever beam models for two-dimensional analysis or the trial load twist method for three-dimensional analysis are appropriate as described in the US Bureau of Reclamation (USBR), "Design of Gravity Dams" (1976). The finite element method is ordinarily used for the feature and final design stages if a more exact stress investigation is required.

b. Finite element analysis.

(1) Finite element models are used for linear elastic static and dynamic analyses and for nonlinear analyses that account for interaction of the dam and foundation. The finite element method provides the capability of modeling complex geometries and wide variations in material properties. The stresses at corners, around openings, and in tension zones can be approximated with a finite element model. It can model concrete thermal behavior and couple thermal stresses with other loads. An important advantage of this method is that complicated foundations involving various materials, weak joints on seams, and fracturing can be readily modeled. Special purpose computer programs designed specifically for analysis of concrete gravity dams are CG-DAMS (Anatech 1993), which performs static, dynamic, and nonlinear analyses and includes a smeared crack model, and MERLIN (Saouma 1994), which includes a discrete cracking fracture mechanics model.

(2) Two-dimensional, finite element analysis is generally appropriate for concrete gravity dams. The designer should be aware that actual structure response is three-dimensional and should review the analytical and realistic results to assure that the two-dimension approximation is acceptable and realistic. For long conventional concrete dams with transverse contraction joints and without keyed joints, a two-dimensional analysis should be reasonably correct. Structures located in narrow valleys between steep abutments and dams with varying rock moduli which vary across the valley are conditions that necessitate three-dimensional modeling.

(3) The special purpose programs Earthquake Analysis of Gravity Dams including Hydrodynamic Interaction (EADHI) (Chakrabarti and Chopra 1973) and Earthquake Response of Concrete Gravity Dams Including Hydrodynamic and Foundation Interaction Effects (EAGD84) (Chopra, Chakrabarti, and Gupta 1980) are available for modeling the dynamic response of linear two-dimensional structures. Both programs use acceleration time records for dynamic input. The program SDOFDAM is a two-dimensional finite element model (Cole and Cheek 1986) that computes the hydrodynamic loading using Chopra's simplified procedure. The finite element programs such as GTSTRUDL, SAP, ANSYS, ADINA, and ABAQUS provide general capabilities for modeling static and dynamic responses.

5-2. Dynamic Analysis

The structural analysis for earthquake loadings consists of two parts: an approximate resultant location and sliding stability analysis using an appropriate seismic coefficient (see Chapter 4) and a dynamic internal stress analysis using site-dependent earthquake ground motions if the following conditions exist:

a. The dam is 100 feet or more in height and the peak ground acceleration (PGA) at the site is greater than 0.2 g for the maximum credible earthquake.

b. The dam is less than 100 feet high and the PGA at the site is greater than 0.4 g for the maximum credible earthquake.

c. There are gated spillway monoliths, wide roadways, intake structures, or other monoliths of unusual shape or geometry.

d. The dam is in a weakened condition because of accident, aging, or deterioration. The requirements for a dynamic stress analysis in this case will be decided on a project-by-project basis in consultant and approved by CECW-ED.

5-3. Dynamic Analysis Process

The procedure for performing a dynamic analysis include the following:

a. Review the geology, seismology, and contemporary tectonic setting.

b. Determine the earthquake sources.

c. Select the candidate maximum credible and operating basis earthquake magnitudes and locations.

d. Select the attenuation relationships for the candidate earthquakes.

e. Select the controlling maximum credible and operating basis earthquakes from the candidate earthquakes based on the most severe ground motions at the site.

f. Select the design response spectra for the controlling earthquakes.

g. Select the appropriate acceleration-time records that are compatible with the design response spectra if acceleration-time history analyses are needed.

h. Select the dynamic material properties for the concrete and foundation.

i. Select the dynamic methods of analysis to be used.

j. Perform the dynamic analysis.

k. Evaluate the stresses from the dynamic analysis.

5-4. Interdisciplinary Coordination

A dynamic analysis requires a team of engineering geologists, seismologists, and structural engineers. They must work together in an integrated approach so that elements of conservatism are not unduly compounded. An example of undue conservatism includes using a rare event as the MCE, upper bound values for the PGA, upper bound values for the design response spectra, and conservative criteria for determining the earthquake resistance of the structure. The steps in performing a dynamic analysis should be fully coordinated to develop a reasonably conservative design with respect to the associated risks. The structural engineers responsible for the dynamic structural analysis should be actively involved in the process of characterizing the earthquake ground motions (see paragraph 5-6) in the form required for the methods of dynamic analysis to be used.

5-5. Performance Criteria for Response to Site-Dependent Earthquakes

a. Maximum credible earthquake. Gravity dams should be capable of surviving the controlling MCE without a catastrophic failure that would result in loss of life or significant damage to property. Inelastic behavior with associated damage is permissible under the MCE.

b. Operating basis earthquake. Gravity dams should be capable of resisting the controlling OBE within the elastic range, remain operational, and not require extensive repairs.

5-6. Geological and Seismological Investigation

A geological and seismological investigation of all damsites is required for projects located in seismic zones 2 through 4. The objectives of the investigation are to establish controlling maximum and credible operating basis earthquakes and the corresponding ground motions for each and to assess the possibility of earthquake-induced foundation dislocation at the site. Selecting the controlling earthquakes is discussed below. Additional information is also available in TM 5-809-10-1.

5-7. Selecting the Controlling Earthquakes

a. Maximum credible earthquake. The first step for selecting the controlling MCE is to specify the magnitude and/or modified Mercalli (MM) intensity of the MCE for each seismotectonic structure or source area within the region examined around the site. The second step is to select the controlling MCE based on the most severe vibratory ground motion within the predominant frequency range of the dam and determine the foundation dislocation, if any, capable of being produced at the site by the candidate MCE's. If more than one candidate MCE produce the largest ground motions in different frequency bands significant to the response of the dam, each should be considered a controlling MCE.

b. Operating basis earthquake.

(1) The selection of the OBE is based upon the desired level of protection for the project from earthquake-induced damage and loss of service project life. The project life of new dams is usually taken as 100 years. The probability of exceedance of the OBE

during the project life should be no greater than 50 percent unless the cost savings in designing for a less severe earthquake outweighs the risk of incurring the cost of repairs and loss of service because of a more severe earthquake.

(2) The probabilistic analysis for the OBE involves developing a magnitude frequency or epicentral intensity frequency (recurrence) relationship of each seismic source; projecting the recurrence information from regional and past data into forecasts concerning future occurrence; attenuating the severity parameter, usually either PGA of MM intensity, to the site; determining the controlling recurrence relationship for the site; and finally, selecting the design level of earthquake based upon the probability of exceedance and the project life.

5-8. Characterizing Ground Motions

a. General. After specifying the location and magnitude (or epicentral intensity) of each candidate earthquake and an appropriate regional attenuation relationship, the characteristics of vibratory ground motion expected at the site can be determined. Vibratory ground motions have been described in a variety of ways, such as peak ground motion parameters, acceleration-time records (accelerograms), or response spectra (Hayes 1980, and Krinitzsky and Marcuson 1983). For the analysis and design of concrete dams, the controlling characterization of vibratory ground motion should be a site-dependent design response spectra.

b. Site-specific design response spectra.

(1) Wherever possible, site-specific design response spectra should be developed statistically from response spectra of strong motion records of earthquakes that have similar source and propagation path properties as the controlling earthquake(s) and are recorded on a foundation similar to that of the dam. Important source properties include magnitude and, if possible, fault type and tectonic environment. Propagation path properties include distance, depth, and attenuation. As many accelerograms as possible that are recorded under comparable conditions and have a predominant frequency similar to that selected for the design earthquake should be included in the development of the design response spectra. Also, accelerograms should be selected that have been corrected for the true baseline of zero acceleration, for errors in digitization, and for other irregularities (Schiff and Bogdanoff 1967).

(2) Where a large enough ensemble of site-specific strong motion records is not available, design response spectra may be approximated by scaling that ensemble of records that represents the best estimate of source, propagation path, and site properties. Scaling factors can be obtained in several ways. The scaling factor may be determined by dividing the peak or effective peak acceleration specified for the controlling earthquake by the peak acceleration of the record being rescaled. The peak velocity of the record should fall within the range of peak velocities specified for the controlling earthquake, or the record should not be used. Spectrum intensity can be used for scaling by using the ratio of the spectrum intensity determined for the site and the spectrum intensity of the record being rescaled (USBR 1978). Acceleration attenuation relationships can be used for scaling by dividing the acceleration that corresponds to the source distance and magnitude of the controlling earthquake by the acceleration that corresponds to the source distance and magnitude of the record being rescaled (Guzman and Jennings 1970). Because the scaling of accelerograms is an approximate operation at best, the closer the characteristics of the actual earthquake are to those of the controlling earthquake, the more reliable the results. For this reason, the scaling factor should be held to within a range of 0.33 to 3 for gravity dam.

(3) Guidance for developing design response spectra, statistically, from strong motion records is given in Vanmarcke (1979).

(4) Site-dependent response spectra developed from strong motion records, as described in paragraphs 5-8*b*, should have amplitudes equal to or greater than the mean response spectrum for the appropriate foundation given by Seed, Ugas, and Lysmer (1976), anchored by the PGA determined for the site. This minimum response spectrum may be anchored by an effective PGA determined for the site, but supporting documentation for determining the effective PGA will be required (Newmark and Hall 1982).

(5) A mean smooth response spectrum of the response spectra of records chosen should be presented for each damping value of interest. The statistical level of response spectra used should be justified based on the degree of conservatism in the preceding steps of the seismic design process and the thoroughness of the development of the design response spectra. If a rare event is used as the controlling earthquake and the earthquake records are scaled by upper bound values of ground motions, then use a response spectrum corresponding to

the mean of the amplification factors if the response spectrum is based on five or more earthquake records.

c. Accelerograms for acceleration-time history analysis. Accelerograms used for dynamic input should be compatible with the design response spectrum and account for the peak ground motions parameters, spectrum intensity, and duration of shaking. Compatibility is defined as the envelope of all response spectra derived from the selected accelerograms that lie below the smooth design response spectrum throughout the frequency range of structural significance.

5-9. Dynamic Methods of Stress Analysis

a. General. A dynamic analysis determines the structural response based on the characteristics of the structure and the nature of the earthquake loading. Dynamic methods usually employ the modal analysis technique. This technique is based on the simplifying assumption that the response in each natural mode of vibration can be computed independently and the modal responses can be combined to determine the total response (Chopra 1987). Modal techniques that can be used for gravity dams include a simplified response spectrum method and finite element methods using either a response spectrum or acceleration-time records for the dynamic input. A dynamic analysis should begin with the response spectrum method and progress to more refined methods if needed. A time-history analysis is used when yielding (cracking) of the dam is indicated by a response spectrum analysis. The time-history analysis allows the designer to determine the number of cycles of nonlinear behavior, the magnitude of excursion into the nonlinear range, and the time the structure remains nonlinear.

b. Simplified response spectrum method.

(1) The simplified response spectrum method computes the maximum linear response of a nonoverflow section in its fundamental mode of vibration due to the horizontal component of ground motion (Chopra 1987). The dam is modeled as an elastic mass fully restrained on a rigid foundation. Hydrodynamic effects are modeled as an added mass of water moving with the dam. The amount of the added water mass depends on the fundamental frequency of vibration and mode shape of the dam and the effects of interaction between the dam and reservoir. Earthquake loading is computed directly from the spectral acceleration, obtained from the design earthquake response spectrum, and the dynamic properties of the structural system.

(2) This simplified method can be used also for an ungated spillway monolith that has a section similar to a nonoverflow monolith. A simplified method for gated spillway monoliths is presented in WES Technical Report SL-89-4 (Chopra and Tan 1989).

(3) The program SDOFDAM is available to easily model a dam using the finite element method and Chopra's simplified procedure for estimating the hydrodynamic loading. This analysis provides a reasonable first estimate of the tensile stress in the dam. From that estimate, one can decide if the design is adequate or if a refined analysis is needed.

c. Finite element methods.

(1) General. The finite element method is capable of modeling the horizontal and vertical structural deformations and the exterior and interior concrete, and it includes the response of the higher modes of vibrations, the interaction effects of the foundation and any surrounding soil, and the horizontal and vertical components of ground motion.

(2) Finite element response spectrum method.

(a) The finite element response spectrum method can model the dynamic response of linear two- and three-dimensional structures. The hydrodynamic effects are modeled as an added mass of water moving with the dam using Westergaard's formula (Westergaard 1933). The foundations are modeled as discrete elements or a half space.

(b) Six general purpose finite element programs are compared by Hall and Radhakrishnan (1983).

(c) A finite element program computes the natural frequencies of vibration and corresponding mode shapes for specified modes. The earthquake loading is computed from earthquake response spectra for each mode of vibration induced by the horizontal and vertical components of ground motion. These modal responses are combined to obtain an estimate of the maximum total response. Stresses are computed by a static analysis of the dam using the earthquake loading as an equivalent static load.

(d) The complete quadratic combination (CQC) method (Der Kiureghian 1979 and 1980) should be used to combine the modal responses. The CQC method degenerates to the square root of the sum of squares (SRSS) method for two-dimensional structures in which the frequencies are well separated. Combining modal maxima by the SRSS method can dramatically overestimate or significantly underestimate the dynamic response for three-dimensional structures.

(e) The finite element response spectrum method should be used for dam monoliths that cannot be modeled two dimensionally or if the maximum tensile stress from the simplified response spectrum method (paragraph 5-9*b*) exceeds 15 percent of the unconfined compressive strength of the concrete.

(f) Normal stresses should be used for evaluating the results obtained from a finite element response spectrum analysis. Finite element programs calculate normal stresses that, in turn, are used to compute principal stresses. The absolute values of the dynamic response at different time intervals are used to combine the modal responses. These calculations of principal stress overestimate the actual condition. Principal stresses should be calculated using the finite element acceleration-time history analysis for a specific time interval.

(3) Finite element acceleration-time history method.

(a) The acceleration-time history method requires a general purpose finite element program or the special purpose computer program called EADHI. EADHI can model static and dynamic responses of linear two-dimensional dams. The hydrodynamic effects are modeled using the wave equation. The compressibility of water and structural deformation effects are included in computing the hydrodynamic pressures. EADHI was developed assuming a fixed base for the dam. The most comprehensive two-dimensional earthquake analysis program available for gravity dams is EAGD84, which can model static and dynamic responses of linear two-dimensional dams, including hydrodynamic and foundation interaction. Dynamic input for EADHI and EAGD84 is an acceleration time record.

(b) The acceleration-time history method computes the natural frequencies of vibration and corresponding mode shapes for specified modes. The response of each mode, in the form of equivalent lateral loads, is calculated for the entire duration of the earthquake acceleration-time record starting with initial conditions, taking a small time interval, and computing the response at the end of each time interval. The modal responses are added for each time interval to yield the total response. The stresses are computed by a static analysis for each time interval.

(c) An acceleration-time history analysis is appropriate if the variation of stresses with time is required to evaluate the extent and duration of a highly stressed condition.